Phase I Project Summary

Firm: CFD Research Corporation
Contract Number: NNX12CF24P
Project Title: Electron Kinetics in Hypersonic Plasmas

Identification and Significance of Innovation:

Development of hypersonic flight vehicles for space exploration poses several design challenges associated with limited understanding of the aerothermal environment at super orbital speeds. This SBIR project aims to advance the state-of-the-art in computations of hypersonic plasmas by adding high-fidelity transport models for electrons to existing Unified Flow Solver. This will enable simulations of plasma properties over entire vehicle trajectories from rarefied to continuum flow regimes. The new capabilities will reduce uncertainty in calculations of ionization processes, enhance predictive capabilities of collisional-radiative models especially in the poorly understood vacuum ultraviolet part of the spectrum, and help analyze the communication blackout problem crucial to spacecraft and hypersonic missiles. Key innovations include: a) using the Fokker-Planck kinetic equation for the Electron Energy Distribution Function (EEDF) in hypersonic plasmas, b) automatic selection of kinetic and fluid models for electrons in different parts of computational domain based on hydrodynamics breakdown criteria, and 3) adaptive modeling of the electric fields using both the quasi-neutrality assumption and the Poisson equation, depending on local flow conditions.

Technical Objectives and Work Plan:

The goal of this project is to add multi-scale model for electron transport to the state-of the art adaptive codes for computations of hypersonic plasmas in rarefied and continuum flow. Specific objectives are:

- Develop adaptive multi-scale model for electrons applicable for hypersonic flows in rarefied and continuum regimes
- Incorporate this model into UFS framework coupled to plasma, chemistry, and radiation transport modules
- Assess predictive capabilities of the new model for reducing uncertainty for calculations of vacuum ultraviolet radiation and other properties of hypersonic plasmas

To accomplish these goals, we add accurate yet efficient adaptive multi-scale model for electron transport to our previously developed comprehensive computational tool for aerothermal environment around space vehicles, the Unified Flow Solver (UFS). The key advantage of this model would be its applicability to a wide range of weakly ionized flows, including hypersonic flows at extreme Mach numbers, expanding nozzle flows, shock wave propagation through plasma, and ionized flow control by externally applied electromagnetic fields. The electron kinetic model will substantially reduce uncertainties in the modeling of plasma chemical reactions and radiation transport in hypersonic flows.

Technical Accomplishments:

During Phase 1, we have developed a new Electron Kinetics Module in UFS framework for solving a Fokker-Planck kinetic equation (FPE) for the Electron Energy Distribution Function (EEDF). We have demonstrated basic functionality of the FPE solver for hypersonic plasma simulations. We calculated the energy spectrum of electrons generated by associative ionization in collisions of hot atoms and validated our model against DSMC simulations of electron energy spectrum in associative ionization on N and O atoms. We have improved our fluid plasma model by adding electron energy balance equation to existing two-temperature multi-species quasi-neutral model, and by adding Poisson and electron number density equations to simulate space-charge effects. Using new capabilities, we demonstrated the formation of a double layer near bow shock and a space-charge sheath near vehicle surface in hypersonic plasmas. We have carried out simulations of hypersonic flows around the RAM-C II and Stardust re-entry vehicles at 61 and 71 km altitudes and have demonstrated good agreement with other codes. We clarified several important properties of hypersonic plasmas and illustrated feasibility of the proposed adaptive multi-scale modeling of electrons by switching between different transport models.

NASA Application(s):

Simulations of the aerothermal environment around space vehicles at extreme Mach numbers. Technology development programs related to access to space and planetary entry. Prediction of thermal load and thermal protection system design for the Orion spacecraft, the proposed Space Launch System, new generation vehicles for space exploration, and components of future hypersonic spacecrafts. Predictive models for plasma radiation signature in the ultraviolet spectral range. Communication blackout problems and hypersonic flow control by electromagnetic fields. Simulation of the extreme aero-thermal environment for entry to Earth, Mars and other planetary atmospheres.

Non-NASA Commercial Application(s):

Technology applications beyond NASA include Ballistic Missile Defense and future hypersonic vehicles performing exo-atmospheric missile intercepts, nozzle expansion and thruster plume interaction. The new model will improve predictive capabilities for calculating the radiation signature of hypersonic plasmas. The tool will have an appeal to rocket engine manufacturers (e.g., ATK, Pratt & Whitney, and Aerojet) and to universities studying arc-jets, plasmatrons and other high enthalpy flow systems. The developed computational tool will be utilized for evaluation of plasma phenomena on advanced hypersonic vehicles such as the X-51 waverider, missile technologies such as the Next Generation Aegis Missile. Typical applications include communication blackout for hypersonic flights, plasma flow control for hypersonic vehicles, hypersonic combustion, electric propulsion, plasma plumes expanding through nozzles, and shock wave propagation through plasmas. The methodology and software will be extendable for analysis of high-speed plasma jets for material processing and biomedical applications, plasma assisted ignition and combustion. Potential users include Air Force, DARPA, and commercial companies utilizing plasma technologies for aerospace, propulsion, combustion, power, material processing, and other applications.

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